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ROTATING POWER SYSTEM STABILIZER

TECHNICAL FIELD

The present invention relates generally to stabilisers in electric power systems and methods for stabilising. The invention relates in particular to stabilisers comprising rotating electrical machines, and control of these.

BACKGROUND

A power network should ideally be a "bus" where different power producers and consumers may connect themselves and deliver/take out the amount of power they need when they so wish. In practise, the power network will not function according to this ideal principle, since there will be limitations for how much power that can be fed in/fetched out at different places and how much power that can be transmitted between different parts of the power network.

Power network is normally referred to as a network where the electric power is transmitted in a 3-phase high voltage alternating current network. However, one may have direct current connections between non-synchronous alternating current networks or internally between two points (nodes) in an alternating current network.

The power limitations for the power network do often not depend on the thermal load capability of the components included in the electric power network, but are typically limited by stability and reliability considerations. The network should be stable, i.e. larger or smaller operation disturbances should be damped out and the network should fall back to a stable state. The power network should also withstand that larger power producers and/or consumers are disconnected without leading to instability or resulting faults that causes the power network to break down.

The power network should also be operated within certain given voltage margins. Several apparatuses, such as transformers and motors are designed for operation within given voltage ranges. The voltage in an alternating current power network is regulated by controlling the reactive power balance in the network. At deficiency of reactive power or at adverse distribution between where reactive power is produced and consumed, the network may at certain occasions not manage to maintain the voltage and a so called voltage collapse is obtained, whereupon the network breaks down.

Synchronous machines are used, besides for energy conversion, also as synchronous compensators without being connected to any driving machine or mechanical load and therefore they do not perform any energy conversion. These machines are rotating synchronously with the power network and may deliver/consume reactive power. Furthermore, they contribute to stabilise the power network at operation disturbances in that the magnetising of the machine is regulated and in that the synchronous compensator increases the short-circuit power of the power network. The capability of a synchronous machine to stabilise the power network by modulating active power is limited by that the active power that can be regulated has to be provided from the magnetic energy in the air gap of the machine or from rotating mass by a transient rotational speed variation when the load angle of the machine is changed.

ASH denotes Asynchronous Hydro (also known as ASG - Asynchronous Generator) and is an asynchronous machine where the rotor winding is fed via slip rings from a current converter that is connected to the same power network as the stator poles of the machine. These machines have their use primarily in connection with pump power stations. The advantages are several, among others that the efficiency of the power station is improved and that one may perform so-called load following in pumping operation, i.e. that the power extraction from the power network can be regulated in

pumping operation. Such machines are in operation at several places in Japan and are described by Takao Kuwabars et. al. in ”Design and dynamic response characteristics of 400 MW adjustable speed pumped storage unit for Ohkawachi power station” in IEEE Transactions on Energy Conversion, Vol. 11, No. 2, June 1996, pp. 376 - 384. An ASH may also be operated as a synchronous machine by feeding direct current to the rotor. However, one should be aware of that this might give thermal overload at one phase if this stationary conducts full magnetising current.

An ASH may be used to improve the stability of the network in that one may rapidly regulate the delivered active power to the network from the machine at operation disturbances or faults in the network. Unlike for a synchronous machine, one may regulate active and reactive power independently of each other. The improvement of the stability of the power network enables a higher utilisation of the power network in that larger amounts of power can be transmitted. This is described by Jan O. Gjerde et. al. in "Integration of Adjustable Speed Hydro Machines in Established Networks", Proc. of Hydropower into the Next Century - III (Hydropower '99), Gmunden, Austria, 1999, pp. 559-567. Another advantage with ASH machines is that the operational power at the current converter is small compared to the total operational power of the machine, typically 15-30 % in plants that have been put into operation.

A problem with the ASH machines of today is that the frequency converter connected to the power network rapidly will be disconnected at operation disturbances. The machine will therefore be sensitive for faults in the power network. This is particularly true when the part of the converter that is connected to the power network requires reactive power in order to commute and in particular when the converter is a cyclo-converter, where also the network power should have a good symmetry between the phases. In two US patents 4,812,730 and 4,870,339, different methods for maintaining a controllable alternating voltage in the stator of the machine at drop-out of

the connected power network are described. This is absolutely necessary in order to maintain the magnetising of the machine so that it can be phased in again when the voltage in the power network returns.

FACTS - an acronym for "Flexible AC Transmission System" is a composite term for several different components comprising power electronics and used for regulating the power flow and voltage distribution in a power network. The definition provided by IEEE (Institute of Electrical and Electronics Engineers) says that FACTS is:

"Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability."

Simplified, FACTS components may be described as equipment, in which in most cases power electronic valve elements (thyristors and transistors) are comprised, in order to rapidly and precisely being able to vary the voltage, current, impedance and/or phase angle in or between the connecting points (nodes) to which the component is connected. Since the introduction of these components creates possibilities to control the power flow, they can be utilised for increasing the transmission capability of the power system between different areas or points. Furthermore, the introduction of the components can reduce the transmission losses in the transmission system by distributing the power flow in a better way between different transmission paths.

FACTS components may be connected to the power network by shunt connections, serial connections or a combined shunt and serial connection.

Shunt connected units are mainly used for input/output of reactive power and power electronic components are then utilised for a rapid regulation of reactive power input/output. One example is SVC - "Static Var

Compensator", which consists of parallel connected reactors (coils) and capacitors and where the power electronics is used to control the reactive power production/consumption to the unit. This is usually performed by controlling the current through the reactors. If a total controllability is desired, i.e. ± 100% of the power to the SVC unit, the power electronic parts should be dimensioned for the total reactive power of the unit. However, a SVC generates harmonics and filtering is therefore necessary. Furthermore, the capability of a SVC to inject reactive current into the power network will be reduced with voltage, i.e. when the need often is as largest. A "Static Synchronous Compensator" (STATCOM), however, has not this problem since shunt connected capacitors and reactors are not a part of the reactive power production/consumption. The reactive power is generated directly by power electronic valve elements and the unit operates in reality as a synchronous compensator without rotating mass and with controllable and limited short-circuit power. However, all reactive power should go through the current converter, so this has to be dimensioned for full power.

Serial connected elements in transmission contexts consist mainly of capacitors and are mainly used to compensate for reactance of a power line, and thus to reduce the "electrical length" of the line. A serial connected capacitor injects a voltage that is phase shifted 90 electrical degrees to the current in the power line. The amplitude of the injected voltage can be controlled, such as e.g. in a thyristor controlled serial capacitor (TCSC).

A UPFC - "Universal Power Flow Controller" - consists of two current converters, one in series and the other one connected in shunt to the transmission system. This leads to that a UPFC may regulate a reactive power that can be injected in shunt with the electric power line as well as a controllable voltage that can be injected in series, which leads to that the voltage both can be regulated in amplitude and phase. A UPFC may thus simultaneously, and independently, control both the active and reactive power flow in a transmission line, and combines thereby possibility for power

control and voltage regulation. UPFC constitutes a flexible tool for control of power flows, at the price of a complex circuit solution with expensive current converters.

FACTS have large dynamics, which makes it possible to use them in order to improve the dynamical properties of the power network. They may also compensate for asymmetric operation, e.g. when the voltage between the different phases are different. An overview of the different FACTS components and their use and state of the art is given in the article "FACTS – powerful systems for flexible power transmission" by R. Grünbaum et. al. in ABB Review, No. 5, 1999, pp. 4-17.

For all FACTS components is generally true that they traditionally do not comprise any energy storage worth mentioning. The energy stored in capacitors and reactors is strongly restricted in comparison with the operational power of the unit and these units can therefore not contribute with or withdraw active power from the power network. By for instance connecting an energy source to the DC side in a STATCOM, this is, however, possible to realise. In existent experimental plants, either batteries (Battery Energy Storage - BES) or superconducting coils (Superconductive Magnetic Energy Storage - SMES) are utilised as energy storage. In an article of Y. Mitani et. al. "Application of Superconductive Magnet Energy Storage to Improve Power System Dynamic Performance", IEEE Transactions on Power Systems, Vol. 3, No. 4, November 1988, pp. 1418-1425, it is shown how such a unit can be used to improve the stability of the power network. A disadvantage both with SMES and BES is that the current converter has to be designed for full power and that the energy storages are expensive and that some types of batteries contain heavy metals and other environment harmful materials.

The placing of different types of compensators in the power network is very important in order for them to have the desired result. In order to stabilise

electromechanical oscillations between generators or groups of generators, shunt connected reactive compensators should for instance be placed at the same electrical distance between the two generators (or groups of generators) to have a good action. In order to improve the reactive balance of the power network should, however, these units be placed in the vicinity of or within large load areas. Shunt connected units that can regulate active power, such as an ASH, should be placed close to other power producers in order to act stabilising.

For all power electronics converters is generally true that their overload capability is limited by short "thermal" time constants. A current converter, for instance, has a very short capability to withstand overload. A current converter should therefore be dimensioned for maximum load of current and voltage.

A power network that has a large portion non-thermal power, e.g. hydropower networks or wind power networks, may be able to experience large season or day variations in power flow of the power network. There is thus a need for being able to use stabilisers that both can compensate for reactive and/or active power so that they can be utilised during different operational conditions in the power network.

A particular embodiment of rotating electrical machines is shown in WO 97/45919, where the high-voltage stator winding is based on cable technology. Any transformer for connection to a high-voltage network is then not needed. Machines designed with this type of stator winding are characterised in that it has very low current density in the stator conductors and in that the cooling substantially is effected at ground potential in the iron packet of the stator. The machines have, by a suitable design of the area and/or protection of the rotor windings, a good capability temporarily, during tenths of minutes or even a few hours, to generate very large reactive power. A design for protection is described in WO 98/34312, where the

temperature of the rotor is represented in a relay protection, stationary positioned in the plant.

A common problem with stabilisers according to the state of the art is that it is difficult to provide stabilisers with sufficient energy storage resources. The costs and the complexity of stabilisers with large capacity are very large, and on purpose one instead selects to only use smaller stabilisers and instead turn off parts of the electric power network if the fault situations become serious enough. Another common problem with stabilisers according to prior art is that they can not in a flexible way be used to compensate for both reactive and active power.

SUMMARY

It is thus a general object of the present invention to provide stabilisers for electric power systems that provides larger energy storage capabilities. Another general object of the present invention is to provide stabilisers that are smaller, more flexible and simpler than the constructions of today.

The above objects are accomplished by devices and methods according to the enclosed patent claims. In general terms, the invention relates to a rotating power system stabiliser, comprising a main machine in form of an asynchronous machine with wound rotor. The rotational speed of the rotor may be varied in order to change the amount of stored energy. The power system stabiliser is characterised in that the stator of the main machine is connected to a power network, that the rotor winding of the main machine is connected to a current converter and in that the current converter collects its active power from a voltage source that preferably is independent of the power network. The voltage source is preferably constituted by a rotating electric regulating machine having a common shaft with the asynchronous machine. The current converter is arranged for control and regulation of the active and reactive power production/consumption of the main machine.

The current converter regulates the current in the rotor winding, whereby the magnetisation and power conversion of the machine is regulated. The current converter is preferably positioned co-rotating with the common shaft of the main machine and the regulating machine.

The shaft of the power system stabiliser can be connected to a flywheel in order to amplify the energy storage capacity of the rotor. The power system stabiliser should primarily be able to damp oscillations in power networks during and after operation disturbances, hence improve the transient stability of the network, and therefore operates actively only during short periods. The power system stabiliser according to the present invention can be overloaded during such a shorter time, which makes it possible to maintain its nominal power, and thereby cost, low. By directly monitoring temperatures in stator and/or rotor windings, the overload utilisation of the electrical main machine can be performed temporarily at large power transmissions, that far exceed the power rating, without risking any damages on the machine.

The power system stabiliser can be used in several manners. It can be used as a shunt connected element in the power network, where it during operation disturbances and at fault states in the power network stabilises the power network by supplying/consuming active and reactive power. The active power is collected/delivered by changing the rotational speed of the rotor of the machine, where mechanical energy is stored as a result of the moment of inertia of the rotor. At normal operation, the rotating power system stabiliser can compensate for reactive power and operates then mainly as a rotating synchronous compensator. The power system stabiliser can furthermore be used as a power converter, where the machine, in addition to the functions above, converts mechanical energy to electrical energy, or electrical energy to mechanical energy, by connecting the shaft of the power stabiliser to a turbine or a mechanical load, respectively.

The power system stabiliser is normally driven close to its synchronous rotational speed. The active electric power that is fed from the current converter to/from the rotor winding therefore only amounts to a small portion of the active electric power that the power system stabiliser feeds to/from the power network. The rotating asynchronous machine therefore constitutes an active power amplifier for the current converter that is connected to the rotor of the machine.

The invention also relates to a method for stabilising of a power system, comprising the main steps of transmitting electric power between a power line and a rotating main machine and regulating this electric power by changing the rotational speed of the main machine.

A device and method according to the present invention have a multitude of advantages. The rotating stabiliser has unlike static compensators a large energy storage in the rotating shaft that can be used to transient input and output of active power for damping of power oscillations in the electric power network. At transient overload of the machine, its properties can be significantly increased. The energy storage can be amplified in a cost efficient way by using flywheels. The rotating stabiliser can unlike traditional rotating compensators compensate for asymmetric operation (minus sequence system). Used as a shunt connected reactive compensator, the machine can within limited periods of e.g. 5 - 60 minutes be overloaded considerably with reactive power in that the temperature margins of the insulation can be utilised in a controlled manner by measuring the temperature in the stator and/or rotor winding. A machine with high-voltage cable winding has, furthermore, a large thermal time constant that implies that the period where the machine is not in thermal equivalence increases. During this period, the load may be increased further. Capability of overloading leads to that the nominal power of the machine can be reduced. The rotating stabiliser has an inner emf that in principle is controllable even at faults in the power network as long as the regulating machine can deliver power to

the current converter. The machine may thereby have a controlled input of active and/or reactive power during transient courses at faults in the power network. The machine therefore has a controllable short-circuit power. The rotor winding may be designed with a frequency-depending resistance so that the capability of the machine to withstand large network disturbances increases. The machine can unlike static compensators for instance be used as combined power converter and compensator in a power station in order to damp oscillations both in power networks and e.g. water paths.

SHORT DESCRIPTION OF THE FIGURES

The invention and further objects and advantages achieved thereby is best understood by reference to the description below and the enclosed drawings, in which:

Fig. 1a is a schematic illustration of a power system stabiliser according to the present invention, comprising a transformer, but without connection to driving machine or load;

Fig. 1b is a schematic illustration of a power system stabiliser according to the present invention, comprising high-voltage cable windings, but without connection to driving machine or load;

Fig. 2a is a schematic illustration of a power system stabiliser according to the present invention, comprising a transformer and connected to a driving machine or load;

Fig. 2b is a schematic illustration of a power system stabiliser according to the present invention, comprising high-voltage cable windings and connected to driving machine or load;

Fig. 3 is a schematic illustration of a first embodiment of a stabiliser according to the present invention, comprising a brushless main machine;

Fig. 4 is a schematic illustration of a second embodiment of a stabiliser according to the present invention, comprising a main machine with brushes;

Fig. 5a is an equivalent scheme per phase of the main machine of fig. 3;

Fig. 5b is a reformulated equivalent scheme corresponding to the one in fig. 5a;

Fig. 6 is a phasor diagram of an operation situation where the stabiliser according to the present invention stationary operates as a synchronous compensator;

Fig. 7 shows the position of the stator flux referred to the winding axes of the stator and rotor windings;

Fig. 8 is a block diagram for control of the stabiliser in a stator flow oriented system with the current converter connected to the rotor of the main machine;

Fig. 9a is a diagram showing power oscillations between a power system stabiliser according to the present invention and an electric power network;

Fig. 9b is a diagram showing rotational speed variations arising in a power system stabiliser according to the present invention at the power oscillations of fig. 9a;

Fig. 10 is a diagram showing non-periodic power oscillations between a power system stabiliser according to the present invention and an electric power network;

Fig. 11 illustrates schematically a power network with one production area and one load area;

Fig. 12 illustrates schematically a power network with two production areas and one load area, where a power system stabiliser is connected to one of the production areas;

Fig. 13 illustrates schematically a power network with two production areas and one load area, where a power system stabiliser is connected to the load area;

Fig. 14 shows how the regulation system for the voltage and power regulators shown in fig. 8 is extended to be able to perform active and reactive power modulation; and

Fig. 15 is a flow diagram illustrating a stabilising method according to the present invention.

DETAILED DESCRIPTION

As stated above, a preferred embodiment of the invention comprises comprehensively a power system stabiliser built by a rotating electrical machine (main machine), where the stator winding is shunt connected to a power network. The rotor winding of the machine is designed as a multiphase alternating current winding and this is fed from a current converter. The current converter is further connected to a rotating machine (regulating machine) mounted at the same shaft as the main machine.

By way of introduction, it is briefly described how the stabiliser is connected to a power network and what powers that can be controlled in order to stabilise the power network. Thereafter, the power carrying parts in the rotating stabiliser are first described, i.e. stator and rotor of the main machine and regulating machine, and the current converter, which is connected between the regulating machine and the rotor winding of the main machine. After this, the control and monitoring of the stabiliser is described and how this is performed by sensors and digital control units positioned in the rotor and/or stator of the machine. Finally, it is stated more in detail how the stabiliser can be driven and used in a power network.

For alternating current machines are generally true that they are made for power conversion, i.e. that they work either as motors or generators. The shaft of the machine is then connected to a mechanical load or a driving machine.

According to a first embodiment, the main machine of the power system stabiliser, as shown in fig. 1a, is in principle an asynchronous machine 2, where the stator winding is a 3-phase alternating current winding connected

to a power network 1 via a transformer 3 and a connection means 4. In fig. 1a, the main machine is not connected to any driving machine ("prime mover") or mechanical load and its possible power exchange with the power network is then:

Q: The stabiliser can stationary supply/consume reactive power to/from the power network. This value can swiftly be changed from a stationary value Q1 to a new stationary value Q2. The maximum power is given by stationary thermal limits in the main machine.

ΔQ: This symbolises the possibility of the stabiliser to, during a limited time interval, at an operation disturbance or fault deliver/absorb a reactive power that can be larger than what is stationary thermally permitted. This is reported on more in detail below.

ΔP: This symbolises the possibility of the machine to, during a limited time interval, deliver/receive active electric power that differs from the shaft power by letting the rotational speed of the machine change. Energy may then be collected from rotating mass by reducing the rotational speed or be stored in rotating mass by increasing the rotational speed. This is reported on more in detail below.

In the embodiment in fig. 1b, the main machine of the power system stabililser is an asynchronous machine 2', where the stator winding is a high-voltage cable winding. The winding is then directly connected via the connected means 4 to the power network without intermediate transformer. In fig. 1b, the main machine is not either connected to any driving machine ("prime mover") or mechanical load and its possible power exchange with the power network is then in analogy with what has been stated in connection with fig. 1a.

The stabiliser can, as in fig. 2a, be connected to a load/driving machine 5. The driving machine supplies mechanical energy to the shaft ("prime mover"). A mechanical load instead collects mechanical energy from the shaft of the stabiliser. The driving machine can for instance be a turbine (water, steam or gas turbine), a combustion machine (piston motor or Stirling machine) or an electrical motor. The mechanical load can be a pump, an electrical generator or brake. When such a machine is connected to the shaft of the stabiliser, it may apart from the earlier mentioned quantities stationary supply or receive active power from the power network, i.e. work as a generator or motor.

In fig. 2b, an asynchronous machine with high-voltage cable winding, connected to a load/driving machine 5 is illustrated. This configuration can in the same manner as above supply or receive active power from the power network.

Sub A7 Fig. 3 shows an embodiment of a power system stabiliser according to the present invention. A main machine 2 is here an asynchronous machine with wound rotor 10. The stator 12 of the main machine has a 3-phase winding 14 connected via a transformer 3 to a power network. The rotor winding 16 can in principle have a number of phases larger than or equal to two. The synchronous rotational speed that is set-up by the 3-phase winding 14 in the stator 12 is determined by the frequency in the power network and by the number of poles that the winding 14 is made with. The rotational speed of the rotor 10 may be changed in relation to this in that an alternating current flows in the rotor winding 16 of the main machine 2. This current is fed by a current converter 18. The frequency of this current is determined by the difference between the synchronous rotational speed, the rotational speed of the rotor and the pole number of the machine. A regulating machine 20 is mounted at the same common shaft 22. The regulating machine 20 is in this example a synchronous machine, where the armature winding 24 is placed in the rotor 26. The co-rotating current converter 18 may therefore

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transfer power between the rotor 26 of the regulating machine and the rotor 10 of the main machine. When the main machine 2 rotates with synchronous speed, all power is transmitted between the rotor 10 and stator 12 of the machine by rotational induction. No active electric power is therefore supplied to the rotor winding 16 at this occasion (if losses are disregarded). When the machine 2 rotates asynchronously, a certain part of the power in the stator 12 will be transmitted transformationly from the rotor 10. This electric energy should therefore be provided to the rotor winding 16 from the current converter 18. The current converter 18 thus makes provision for the magnetising of the main machine 2 and for supplying/receiving regulating power (active electric power) to/from the rotor winding 16 from/to the main machine 2. The task of the regulating machine 20 is to operate as a voltage source for the current converter 18 so that it can magnetise the main machine 2 and to transmit the regulation power into mechanical power on the common shaft 22 in that it alternately works as motor or generator. In a preferred embodiment, the regulating machine 20 works in operation as synchronous machine. The regulating machine 20 can have another pole number than the main machine 2 so that the frequency in this can be increased. The regulating machine 20 presents direct current fed field windings 34 in the stator 28. These are supplied in normal operation via an alternating - direct current converter 42 connected to the same three-phase lines as the stator windings 14 of the main machine, via a transformer 44. At drop-out of the connected power network or other types of operation disturbances, the field winding of the regulating machine can be supplied from a battery back-up 65 or by providing the regulating machine with permanent magnets. In the first case, the converter will be an UPS (Uninterruptable Power Supply).

In fig. 5a, the equivalence scheme of the main machine per phase is shown. One here disregards from the resistance in the stator and rotor winding. X_M is the magnetising reactance, while X_{LS} denotes the leakage reactance in the stator winding and X_{LR} is the leakage reactance in the rotor winding. I_M

denotes the magnetising current, Is the current through the stator windings and I_R the current through the rotor windings. s denotes the slip of the rotor in relation to the synchronous rotational speed of the stator flux. The stator has a generatoric reference, while the rotor has motoric reference.

The power system stabiliser normally operates with a rotational speed, which is close to the synchronous. From the equivalence scheme, it can then be noticed that the voltage in the rotor winding is low, since the slip s is very small. If the stabiliser is to be driven within a rotational speed range, such as ±10% of the synchronous, the share of active electric power that should be supplied to the rotor winding 16 will not exceed 10% of the one of the main machine. This means that the power to the current converter becomes small in relation to the total power of the main machine (and thereby of the stabiliser). Furthermore, the current converter should be able to magnetise the main machine of the stabiliser, which means that the power of the current converter has to be somewhat larger. The power of the regulating machine is therefore determined by maximum regulating power and by the required reactive power of the current converter.

Fig. 4 shows an alternative embodiment according to the present invention. It resembles in large the earlier described embodiment and common parts will not be described again. The armature winding 24' of the regulating machine 20' is in this case placed in the stator 28. The current converter 18' is stationary and connected to the rotor winding 16 of the main machine 2 via brushes 30 and slip rings 32. The field winding 36 of the regulating machine 20' is consequently arranged at the rotor 26 and is supplied with current from the alternating - direct current converter via brushes 38 and slip rings 40.

Fig. 5b shows a reformulated equivalence scheme for the asynchronous machine with wound rotor, where X_M is the magnetising reactance, while X_{LS} denotes the leakage reactance in the stator winding. The sum of these

constitutes the reactance of the stator winding and is denoted by X_A. The value and phase of the rotor current I_R is related to the stator side of the machine.

Fig. 6 shows a phasor diagram of an operation situation where the stabiliser stationary operates as a synchronous compensator. No mechanical driving machine or load is connected to the shaft. The limit of the maximum emitted stationary reactive power is then normally given by the thermal load in the rotor. It is therefore normally the need of magnetomotoric force (MMF) in the rotor that determines the main dimensions of the machine. When the stabiliser operates as a compensator for reactive power, the rotor current may be derived from fig. 5b to:

$$I_R = \frac{U_S}{X_M} + \frac{Q}{U_S}(1 + \frac{X_{LS}}{X_M})$$

From this, one notices that the need for magnetising (the rotor current I_R) becomes lower with higher magnetising reactance X_M. Starting from this, the machine should have high magnetising reactance and low leakage reactance in stator. Compared with a conventional synchronous compensator based on a conventional synchronous machine, one realises that the need of MMF becomes lower than what normally is allowed in a conventional synchronous machine. This depends among other things on the demands for stability at disturbances in the power network. Since one may, via the current converter 18 connected to the rotor winding 16, control the rotor current in amplitude and phase, the rotor and stator flux in this machine will not become asynchronous. One does therefore not loose synchronism as in a conventional synchronous machine, and the demands for stability may be moderated and thereby one reduces the need of MMF in the rotor compared with a conventional synchronous compensator. This means that in order to dimension the stabiliser for stationary reactive power compensation, one may, compared to a conventional synchronous machine, manufacture the

machine with smaller dimensions. This results from that it is the rotor that is dimensioning for the machine and/or that one may reduce the losses in the rotor by reducing the current density in the rotor winding.

Faults in the power network, such as a short-circuiting or ground fault, will normally lead to a disturbance in the operation of the power network. When the fault still is present in the network, the currents will increase and the voltages will drop in the power network. The change is of course largest close to the fault position. During the time the fault is present, synchronous machines in the power network will get their torque balance changed since the electrical load torque is changed while the mechanical one is approximately unchanged. The transient courses in a power network are very complex, so that it for instance could be desirable to supply the network with reactive power while the fault remains, in order to maintain a best possible torque balance. At other occasions, this is not desirable, since the fault currents then will become too large. One may then in contrary have a request to limit both the active and reactive power (current) fed in at faults. Since the current converter 18 in figure 3 is fed from the regulating machine 20, the feeding to the current converter 18 will not be influenced by the fault. The current converter 18 may therefore itself, during a fault in the power network, supply the rotor winding 16 with desired current and voltage. In this way, one may control the input reactive power from the stabiliser during fault situations.

In traditional ASH, as described earlier, the current converter will disconnect at a too large reduction of the voltage in the power network and/or at large asymmetry. In the stabiliser according to the invention, one has in contrary a controllable short-circuit power during the entire fault course. In a traditional synchronous compensator, one will furthermore normally only be able to control the short-circuiting current after that the subtransient course of events has come to an end. Also after this, the dynamics in the control in a synchronous machine is limited as a result of the large time constant of

the field winding. The connection between the voltage of the field winding and the inner voltage of the machine may be regarded as a first order system with a characteristic time constant. This time constant is the transient reactance of the machine at open stator poles and is substantially determined by the field winding. This is denoted in the literature as T'_{d0}. This has a magnitude of 1-8 seconds for large synchronous machines. Since the main machine in the rotating stabiliser is an asynchronous machine, the rotor winding is, unlike in a synchronous machine, designed as an alternating current winding. This has a longer time constant and one may besides changing the amplitude of the current also change its phase.

In order to further increase the robustness of the stabiliser at faults and to increase its damping capability, the rotor winding 16 may be designed so that its inner resistance increases with the frequency of the current. This is performed by utilising the leakage flow in the rotor in order to give a current displacement, i.e. that the current in the rotor winding 16 is not evenly distributed over its cross-section, but is packed together towards that part of the winding 16 that is placed closest to the air gap in the machine. This effect increases with frequency.

Usually, one will disconnect the line where there is a fault. The rotating stabiliser will no longer be connected to the power network if it is connected to the power line that is disconnected. The control system of the power network will as a rule try to perform a fast reconnection, after that the line first has become disconnected. It is then important that the stabiliser can behave analogously to a traditional synchronous generator, so that it again can be phased in at the network. The stabiliser according to the invention has an own separate power network in the rotor, comprising the rotor winding 16 in the main machine 2, the current converter 18 and the regulating machine 20. Since the regulating machine 20 does not loose its magnetising, kinetic energy in the rotating parts may be utilised to magnetise the system and to supply power to the rotor itself of the main

machine if the outer power network is disconnected. The magnetising of the regulating machine does not require any large power and it may as mentioned earlier furthermore be secured by supplying it with a battery back-up 65, or by designing the regulating machine 20 with permanent magnets. Even if the outer power network should drop out during a certain time (in worst case some minute), the voltage in the main machine 2 of the stabiliser may be regulated to correct frequency and phase so that automatic connection can be performed. When it is detected that disconnection has occurred, one may let the control system of the stabiliser (which is described in more detail below) generate a reference value for the stator flux, for instance so that it rotates with the same speed as before the fault.

From fig. 6 one notices that when the stabiliser operates as a compensator close to its nominal power, an increase in active power ΔP or in reactive power ΔQ easily lead to an overload of the machine. Nominal powers are today normally set according to the recommendations of the manufacturer, perhaps with a certain margin. Furthermore, the manufacturers' recommendations usually concern stationary situations, where the temperature of the surroundings, etc. is assumed to be higher than normal. Furthermore, the manufacturers themselves usually give the recommendations with certain margins. In most electrical machines and transformers of today, there is thus normally certain thermal margins that may be utilised for overloading an electrical machine, at least temporarily. In order to prevent that the main machine is damaged when this is performed, the temperature in the rotor and/or stator winding may be monitored during operation by means of temperature sensors. In fig. 3, the main machine is thus provided with a temperature sensor 60 on the rotor winding 16 and a temperature sensor 64 on the stator winding. The machine in fig. 4 is in a similar way provided with temperature sensors 60, 64. This makes it then possible that during a limited time period operate outside the nominal capability of the machine, as stated in fig. 6.

Compared with existing shunt connected compensators according to the prior art this means that the capability of the stabiliser to deliver/consume reactive power in a cost efficient way may be increased far beyond the nominal power of the stabiliser during a shorter period of time. In a SVC, this is not possible, but the entire construction has to be dimensioned to its peak power. Overload capability is therefore not possible. For a STATCOM construction, the entire reactive power should be delivered through a power electronics converter. This has in contrary a very small overload capability. This means that the construction has to be dimensioned for its peak power. In the power system stabiliser according to the invention on the contrary, only the frequency converter should be dimensioned in order to manage the increased rotor power. Since the total power of this converter is low in relation with the total power of the stabiliser, the expenses becomes correspondingly lower.

The stabiliser may also deliver/consume active power to/from the power network. This may be done by changing the rotational speed of the stabiliser and/or by having a driving machine/mechanical load connected to the stabiliser. First, an embodiment where the machine does not have any driving machine or mechanical load connected to its shaft is described, which corresponds to the systems in fig. 1a and fig. 1b.

The energy that is stored in the rotating parts of the stabiliser is largely determined by the moment of inertia and the rotational speed. For electrical machines, it is often expressed in the time constant H for the inertia of the machine, given by:

$$H = \frac{1}{2} \cdot \frac{J\omega_0^2}{S_N}$$

where J represents the moment of inertia of the machine, ω_0 nominal mechanical rotational speed (rad/s) and S_N the power of the machine. H

therefore represents the amount of stored energy in rotating parts at nominal rotational speed in relation to the power of the machine. For larger electrical machines, this is typically in the range of 2-8 seconds.

Fig. 9a shows a course for emitted power P from the power system stabiliser. The power varies between P_0 and $-P_0$, but the average value of the power is zero. When the power oscillates according to a sinus function as in fig. 9a, the converted energy A_1 in one half period will be $\left(2/\pi\right)PT$, where P is maximum active power and T is the period time of the oscillation. During next half period, the same energy A_2 will then be converted again, but now in opposite direction. The rotational speed at such a process will then get a course as given in fig. 9b. A typical period time for power oscillations based on pole ring oscillations, depending on speed oscillations between rotational speed of synchronous machines, in synchronous machines is 0,5 - 2 seconds. For a sinus varying power variation such as in fig. 9a, the need for an energy storage then becomes between 0,32 P and 1,3 P. In the article "Application for Superconducting Magnet Energy Storage to Improve Power System Dynamic Performance", by Y. Mitani et. al in IEEE Transactions on Power Systems, Vol. 3, No. 4, November 1998, pp. 1418-1425 and in the article "Active-Power Stabilizers for Multimachine Power Systems: Challenges and Prospects" by I. Kamwa et. al. in IEEE Transactions on Power Systems, Vol. 13, No. 4, November 1998, is further reported for the amount of energy that should be possible to be stored in relation to the power of the stabiliser. It is then shown that even with en energy storage for E<P, where E is stored energy measured in Joule and P is power measured in Watt, one may get a sufficient damping of oscillations in the power network. Now assume, that the rotational speed variation is ±10% from the synchronous rotational speed. This means that about 20% of the rotating energy may be made useful for stabilisation, which means that the constant of inertia H should be in the order of magnitude of 1,6 - 6,5 seconds for this example. If the stabiliser does not have enough natural moment of inertia, this may be

increased in a cost-efficient way by using flywheels on the stabiliser. This is schematically shown in fig. 3 with the reference numeral 72. This will have its largest use for fast rotating machines, hence where the rotational speed is high, since one then stores more energy in a flywheel with the same physical dimensions. As is evident from the article "Large-Scale Active-Load Modulation for Angle Stability Improvement" by Kamwa et. al., IEEE Transactions on Power Systems, Vol. 14, No. 2, May 1999, pp. 582-590, one typically only needs to modulate 5% of the active power. This means that a power of 1000 MW in a power line may be stabilised by modulating a power of 50 MW. The rotating stabiliser thus provides a cost-efficient energy storage with a capacity for E in the same order of magnitude as P and when one furthermore takes into account that the stabiliser according to the invention may be considerably overloaded, one realises how powerful the stabiliser is in relation to its nominal electric power. It is only the current converter connected to the rotor windings of the main machine that should be up-dimensioned in power, but this converter constitutes only a small share of the total power of the stabiliser.

For occasions where the frequency of the oscillation is so low, that the need of modulated energy is large in relation to the power, one may use mechanical loads. In fig. 4, a brake 70 is arranged at the rotor shaft 22. This brake 70 may be used in order to get rid of too high rotational energies. This increases the flexibility of the stabiliser further, by letting the average value of extracted power from the power network be different from zero and at need getting rid of excess energy via the brake 70. The brake 70 may at need be designed with cooling devices, which make it possible to stationary, during a period of several minutes, utilise the brake 70.

Fig. 10 shows another course for emitted active power P from the power system stabiliser. The power varies non-periodically, but the power is controlled at every occasion according to the needs. The rotational speed for the power system stabiliser will also vary non-periodically as a result of the

power flows. The integral below the power curve corresponds in the same manner as above to the energy that has been given away to the electric power system. As long as this integral remains less than the allowed rotational speed variation in the stabiliser, no energy has to be supplied to or removed from the stabiliser. However, if the power oscillations are too large, a driving machine or a load has to be connected to the shaft of the stabiliser, in order to moderate its rotational speed.

In fig. 3 are also the main parts in the control and monitoring systems illustrated. A static control unit 48 is arranged to supply the alternating - direct current converter 42 with control signals via a control connection 52. The alternating - direct current converter 42 provides the field winding 34 of the regulating machine with suitable magnetising current. In a corresponding way, a rotating control unit 46, which is arranged co-rotating with the common shaft 22 and thereby with the rotor 10 of the main machine, is arranged in order to provide the current converter 18 with suitable control signals via a control connection 66. The current converter 18 thereby provides the rotor winding 16 of the main machine with current of appropriate phase, amplitude and frequency. How this control is performed is described more in detail below. The co-rotating control unit 46 further comprises a communication means 54 for wireless communication with a communication means 54 in the static control unit 48. The control units 46 and 48 may thus exchange information. Both control units 46, 48 comprise process units 47, 49 for processing of signals and data.

The co-rotating control unit 46 is connected to the temperature sensor 60 and is supplied there through with temperature data about the rotor winding. Furthermore, there is a sensor 58, for measuring of current/voltage in the rotor winding to the main machine, and a sensor 62, for measuring of current/voltage in the winding to the regulating machine, connected to the control unit 46, which monitor the current and/or voltage to the rotor

windings 16 and current and/or voltage between the regulating machine 20 and the current converter, respectively.

The static control unit 48 is in a similar way connected to the temperature sensor 64 for measuring of the temperature of the stator winding. Furthermore, a sensor 50 is connected to the control unit 48 for measuring of current and/or voltage to/from the stator 12 of the main machine. With knowledge about the properties of the transformer 3, this sensor 50 indirectly senses the properties of the power network. Alternatively, a sensor 51 may be arranged at the power network side of the transformer 3, thus in the electric power plant, in which the stabiliser is positioned, for direct measurement somewhere in the electric power plant. However, such a solution normally requires, as a result of the higher voltages, more expensive technical solutions. The sensor 50 or the sensor 51 may thus detect disturbances in the power network, e.g. relating to the root mean square (RMS) value, phase and/or amplitude of the voltage and/or the RMS value, phase and/or amplitude of the current, and their frequency.

In this way, data may be obtained regarding electric as well as thermal parameters, and this data is communicated between the control units 46, 48, preferably via a radio connection. The co-rotating control unit 46 may therefore be provided with currently valid information as basis in order to control the rotor current through the current converter 18 in a suitable manner.

I fig. 4, corresponding control units 46, 48 are shown. The rotating control unit 46 is here mainly responsible for collection of data from the temperature sensor 60 and the sensor 58. This data is processed in the process unit 47 and is transmitted wireless over to the static control unit 48. The static control unit 48 is here responsible for the control of both the alternating - direct current converter 42 and the current converter 18'.

The stabiliser according to fig. 3 thus has an integrated control and regulating system, which comprises rotating 47 and stationary 49 digital processors with brushless digital communication 54, 56 and sensors 50, 51, 58, 60, 62, 64 for measuring and monitoring of currently valid quantities. The processors 47, 49 normally operate in a master/slave relation with the rotating processor 47 as slave. Substantially, the stationary processor 49 controls the power conversion, measures and monitors quantities associated with the stator 12 of the electrical machine and communicates with other exterior control and regulating systems. The main task for the rotating processor 47 is to control the, with the shaft of the electrical machine rotating, current converter 18, and measure and monitor quantities associated with the rotor 10 of the machine.

The rotating processor 47 is programmed such that it at repeated and severe disturbances in the wireless digital communication 54, 56 during a period autonomously may control and regulate the stabiliser.

The main machine may be regulated according to the same principles that normally are utilised for ASH machines. The regulation method may be based on a so-called α-β-transformation, where the dynamic equation system of the machine and physical currents and voltages in the rotor and stator are transformed to a system consisting of fictitious rotor and stator windings oriented in a certain manner in relation to the flux of the stator. One may then show that one component of the rotor current controls torque and thereby active power P while the other component controls the pole voltage of the stator and thereby reactive power Q. The regulator structure for this is shown in fig. 8, where 91 is a voltage regulator or regulator for reactive power and 92 is a regulator for active power. The current regulator is denoted by 90. The voltages u_{ar}, u_{br}, u_{cr} are connected to a modulator in the converter. A closer description is given in "Consequences of introducing Adjustable Speed Hydro (ASH) in Established Power Networks", Proc. of PSCC'99, Vol. 1, pp. 150-156, Norwegian Univ. for Technology and Science,

Trondheim, 1999 by Jan O Gjerde et. al. When the stabiliser is connected to a turbine and operates as generator, the rotational speed is controlled by the turbine, having a control system of its own. Examples of this is shown in the publication "Design of dynamic response characteristics of 400 MW adjustable speed pumped storage unit for Ohkawachi Power Station", IEEE Transactions on Energy Conversion, Vol. 11, No. 2, June 1996, pp. 376-384, by T. Kuwabara et. al.

Computation of turn-on and turn-off times for the current converter connected to the rotor may be performed such as shown in figure 7. The position of the stator flux (Ψs) in relation to the stator windings υ_s may be determined in several ways, for instance by mounting sensors in the air gap of the machine or by integrating measured stator voltage. By integrating the measured rotational speed, the position υ of the rotor in relation to the stator is achieved. Thereby, υ_r may be calculated and the α and β component of the rotor current may be transformed to real phase currents in the rotor. The rotational speed of the machine may for instance be measured/calculated by integration of the voltage from the regulating machine.

Measuring of voltage values in high voltage equipment is costly since one needs measurement equipment that is connected to high-voltage conductors and which therefore has to be insulated against these voltages. For electrical machines with high-voltage stator winding, it is costly to equip the machine with its own voltage transformers for measuring of pole voltage, while measuring of current is cheap since it is not necessary to be galvanically connected. Normally, a voltage measurement on the poles of the machine is needed in order to be able to phase it in on the power network when it will operate as a generator. At the bus bar, there will always be voltage measurement since this is necessary for phasing-in of other lines and machines etc. The stabiliser according to the invention may be phased-in towards an exterior power network without measuring of its own of the voltage on the poles of the machine. The measurement of the voltage that

machine should be phased-in towards is transferred to e.g. the stationary computer. This computer then calculates the position of the stator flux in order for the voltage to be in phase with the measured voltage. Thereupon, one may by controlling amplitude and frequency and phase to the rotor current generate a voltage out from the machine, which is in phase with the measured. This represents a clear improvement in relation to prior art since one does not need any voltage transformers of ones own for phasing-in. Since the dynamics in the machine is considerably faster than to the driving machine, this does not have to run stable at a rotational speed which coincides with the synchronous one, since the difference between the synchronous rotational speed and the real rotational speed of the stabiliser may be compensated for by controlling the frequency of the rotor currents. This is not possible for a synchronous machine.

By having a rotating digital control unit and a communication line between rotor and stationary parts of the stabiliser, one may use advanced monitoring systems in the rotor, even if these require extensive signal treatment. Partial discharges in the insulation may, when the discharge level becomes too large, destroy the insulation, which may lead to breakdown. In the publication "Continuous On-line Partial Discharge Monitoring of Power Generators", 1996 IEEE Annual Report – Conference on Electrical Insulation and Dielectric Phenomena, pp. 496-499 by A. Kheirmand et. al., a system INTECH is described, which during operation should be able to monitor the level of partial discharges in the stator winding of a rotating alternating current machine. A similar system may, when one has a rotating digital control unit, also be utilised for monitoring the insulation in the rotor.

The rotating stabiliser according to the invention is flexible in its use. In order to exemplify this, there will be given an account of how it is used in a power network. In fig. 11 a power network comprising mainly one production area 80 and a load area 82 is described. In order to efficiently be able to stabilise power oscillations between these areas, a turn-on means 84A, 84B

may be connected to the power network. Modulation of active power will be most efficient when the turn-on means is positioned close to a producer 88, such as the turn-on means 84A, or a consumer 86 of active power, such as the turn-on means 84B. The stabiliser may then be positioned either in the production area 80 or in the load area 82. If the stabiliser 84A is placed in the production area 80, it may additionally be used as power converter by connecting it to a turbine. If the stabiliser 84B is placed in the load area 82, it may for instance additionally operate as synchronous compensator. Its overload capability results in that it at danger of voltage collapse may be overloaded considerably during a critical period of typically 1 - 30 minutes.

Power oscillations may arise in electric power networks as a result of poorly damped low frequency (for example 0,1 to 2 Hz) oscillations between the rotors of generators. There are two main groups of oscillatory problems characterised in that the oscillations take place either between different areas (inter-area) or more locally (intra-area). The introduction of power system stabilisers (PSS, Power System Stabiliser) on generators may actively contribute to damp power oscillations. A large part of the damping torque, regarding power oscillations between areas, arises via a modulation of the loads of the electric power network.

Damping of (inter-area) oscillations is performed by increasing the damping for the oscillation modes that are of interest, which ideally is performed by applying a braking torque proportional to the speed difference in the machine. Two practical alternatives to stabilise via the magnetising regulation of electrical machines are to modulate the electric or mechanic torque. In practice, an improved damping may be achieved in that a power system stabiliser, PSS, is allowed to give an additional signal to the magnetising system of the machine. The input signals to a PSS may for instance be constituted by speed difference on the rotor shaft, the frequency at the terminal of the generator or the integral of the electric power.

The positioning of devices for stabilising of the power network is a complex topic, which at each occasion needs an extensive analysis. However, one may, based on simplified models, understand how one should try to use different devices. In the article "Utilising HVDC to Damp Power Oscillations" by T. Smed and G. Andersson, IEEE Transactions on Power Delivery, Vol. 8, No. 2, April 1993, pp. 620-627, some instructions are given. Devices that mainly can modulate active power should be placed close to consumers or producers of active power, while devices that mainly can modulate reactive power should be put in an electric midpoint between producers/consumers of active power. The network frequency provides according to the article a suitable input signal for the control of the active power modulation while the derivative of the voltage amplitude provides a suitable input signal for the reactive power modulation.

The instantaneous value for active electric power from the main machine of the stabiliser may for instance be calculated by multiplication of measured instantaneous values of current and voltage belonging to the same phase. The reactive power from the main machine of the stabiliser may be calculated by measuring of the RMS values of current and voltage and the phase angle between current and voltage belonging to the same phase.

Fig. 14 shows how the regulation system in fig. 8 may be changed for this purpose. The signals ΔU and $\Delta\omega$ are treated in their own filters/signal processors denoted by its transfer functions G_p and G_u. These are then generating a signal ΔQ, which represents a transient change of the stationary reference for the voltage/reactive power of the stabiliser, and a signal ΔP, which represents a transient change of the reference for the active power of the machine.

In fig. 12, there is a power network with two production areas 80A and 80B and one load area 82. Now, suppose that these production areas 80A, 80B are different in day and/or season variation. If the production area 80A is

based on hydroelectric power with large reservoirs, this will be dominating in the winter. The power will then mainly flow from the production area 80A to the load area 82. The production area 80B may be based on for instance hydroelectric power with river power plants. Its production is then largest at large discharge in the stream, e.g. in the spring. One will then substantially have a power flow from the area 80B to the load area 82. By positioning a stabiliser 84 in the area 80B, it may itself be utilised if one has season variations in the power flow as described. When the production area 80A dominates, the stabiliser 84 will be able to deliver reactive power to the power network in order to accomplish an optimum voltage distribution in the power network. At faults, the stabiliser can deliver a regulated temporary reactive power ΔQ in order to stabilise active power oscillations between the production area 80A and the load area 82. When the production area 80B is dominating, one may as in figure 11 modulate the active power in order to stabilise oscillations between the production area 80B and the load area 82.

Fig. 13 describes a power network with two dominating production areas 80C, 80D, which feed power into a larger load area 82. Here, the stabiliser 86 may be utilised stationary as synchronous compensator and deliver reactive power in the load area 82, deliver a temporary reactive power ΔQ for stabilising of oscillations between the two production areas 80C, 80D, and to deliver a temporary active power ΔP in order to stabilise oscillations between the load area 82 and one of the production areas 80C or 80D. An example of this is given in the article "Large-Scale Active-Load Modulation for Angle Stability Improvement" by I. Kamwa et. al., IEEE Transactions on Power Systems, Vol. 14, No. 2, May 1999, pp. 582-590.

Fig. 15 shows a flow diagram, which in a simple manner summarises the control method according to the invention. The process starts in step 100. In step 102, a power is transmitted either from the main machine of the stabiliser to the power network or from the power network to the main machine of the stabiliser. In step 104, this power transmission is regulated.

The regulation is performed by changing the rotational speed of the main machine. This is accomplished by sending a current of appropriate frequency, phase and amplitude through the rotor windings of the main machine. The process is ended in step 106.

The skilled man in the art understands that different modifications and changes may be performed at the present invention without deviation from the scope of the invention, which is defined by the enclosed patent claims. It is e.g. possible that instead for a co-rotating regulation machine use another type of current source. In order for the stabiliser to keep its good properties at faults in the power network, this voltage source should be independent from the power network. The voltage source may e.g. be constituted by some energy storage or separate machine. The separate machine may be of any type capable of giving required currents and voltages to control the rotor of the main machine. It may very well have a shaft, which is separated from the main machine, even if certain exclusive features then are made impossible.